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The primary objective of this project is tile formulation and analysis of canonical boundary value problems modeling dynamic fracture in elastic and viscoelastic material. The selection of specific problems is guided by a number of goals. (1) One goal is to understand and model a number of surprising experimentally observed features of dynamic crack propagation in brittle polymers that are not predicted by classical linear elastic fracture mechanics. (2) Another goal is to solve dynamic fracture boundary value problems incorporat-ing a crack tip cohesive zone whose constitutive law is derived from micromechanical models of the physical processes occurring at the tip of a growing crack in a brittle polymer. (3) A third goal is to develop combined analytical and numerical solution schemes for the above canonical dynamic fracture boundary value problems which can be used to benchmark and test direct numerical methods for solving such problems.

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CRACK PROPAGATION IN LINEAR AND NONLINEAR VISCOELASTIC MATERIAL

GRANT NO. F49620-96-1-0294

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Objectives.

The primary objective of this project is the formulation and analysis of canonical boundary value problems modelling dynamic fracture in elastic and viscoelastic material. The selection of specific problems is guided by a number of goals.

1. One goal is to understand and model a number of surprising experimentally observed features of dynamic crack propagation in brittle polymers that are not predicted by classical linear elastic fracture mechanics.
2. Another goal is to solve dynamic fracture boundary value problems incorporating a crack tip cohesive zone whose constitutive law is derived from micromechanical models of the physical processes occurring at the tip of a growing crack in a brittle polymer.
3. A third goal is to develop combined analytical and numerical solution schemes for the above canonical dynamic fracture boundary value problems which can be used to benchmark and test direct numerical methods for solving such problems.

Status of Effort and Accomplishments.

Over the past year, progress was made on two problems begun the previous grant year and two additional problems begun this year as described below.

Nonlinear, Rate Dependent Cohesive Zone Model. The motivation for this problem is the desire to understand and model certain features of dynamically growing cracks in brittle polymers seen by several experimental groups over the past 15 years that cannot be explained by the classical fracture mechanics of brittle materials. Specifically, classical brittle fracture mechanics is based upon the concept of a Critical Energy Release Rate (ERR) as a material parameter. While very successful when applied to quasi-static (slow) crack growth in brittle materials, this concept fails when applied in simplistic fashion to dynamic fracture. In particular, when applied to dynamic fracture boundary value problems, classical fracture mechanics predicts that under constant loading, a crack tip should smoothly accelerate up to the relevant wave speed (the Rayleigh wave speed for mode I fracture and the shear wave speed for mode III fracture). However, experimentally observed crack speeds rarely exceed 40% of the relevant wave speed, and there seems to be a critical crack tip speed beyond which a dynamic instability is initiated that is characterized by high frequency crack speed oscillations. This crack grow instability is associated with increasing crack surface roughness and acoustic emissions.

The P.I., in collaboration with Francesco Costanzo (Engineering Science, Penn State), developed a combined analytical and numerical method for solving the dynamic fracture problem of a semi-infinite, mode III crack in elastic material in which the classical sharp crack tip is replaced by a cohesive zone crack tip model. They employed

a nonlinear-rate dependent cohesive zone constitutive model proposed by material scientists as a model for the craze zone that (always) evolves at the tip of a crack in brittle polymers. The P.I. and Constanzo observed in simulations run using their solution procedure, that their model does indeed predict limiting crack speeds well below the speed of shear waves. The central physical notion captured by the model they employ is that the nonlinear, rate dependent cohesive zone constitutive law reflects dissipative physical processes occurring at a crack tip in brittle materials that classical fracture mechanics doesn't account for.

Unfortunately, this model doesn't predict the crack speed instability observed experimentally. However, Costanzo and the P.I. observed in their simulations (contained in the papers [1, 2]) that due to the rate dependence in the cohesive zone constitutive law, there exists a critical crack tip speed beyond which the maximum value of the cohesive stress exceeds the theoretical strength of the material. Thus, the cohesive zone constitutive law becomes invalid beyond this critical crack tip speed. Nevertheless, these simulations suggest a physical mechanism for the development of a zone of microcracks in front of a dynamically propagating crack tip in brittle materials, as has been conjectured from postmortem examination of fracture surfaces. More specifically, Costanzo and the P.I. offer the following picture of dynamic fracture in brittle polmers.

Upon the application of crack face loads, the high stresses at a crack tip cause a craze zone to form (modelled as a cohesive zone in our simulations). Under continued loading, the crack tip region then smoothly accelerates until the cohesive stress (due to its rate dependent constitutive law) first exceeds the cleavage stress for craze fibrils. Up until this point, the cohesive zone advances according to the *Critical Crack Opening Displacement* criterion, that is, the trailing edge of the cohesive zone advances so as to keep the crack face separation at that point below some critical maximum value (taken to be the mean length of polymer chains, for example). Where the cohesive stress first exceeds the cleavage stress for fibrils is the place where a microcrack first opens within the craze zone. Simulations show this location to always be strictly inside the cohesive zone and to get nearer the trailing edge as crack speed increases. Once a microcrack opens, the remaining ligament of craze material between the microcrack and the trailing edge of the cohesive zone very quickly fails entirely. Since the trailing edge of the cohesive zone, called the *Material Crack Tip*, is the crack tip observed experimentally, an experimentalist would record a sudden acceleration of the crack tip as the ligament of material fails and the new location of the trailing edge of the cohesive zone leaps ahead to the forward edge of the recently created microcrack. It will then take some time for the loading information to reach the new trailing edge of the cohesive zone, causing the apparent crack speed to suddenly drop. Under continued loading the process will repeat giving rise to the sort of oscillating crack tip instability seen experimentally. Costanzo and the P.I. are currently writing the code to simulate this process.

Dynamically Interacting Crack Tips. The P.I., in collaboration with his Ph.D. student Tanya Leise (who received her Ph.D. in December, 1998), have been addressing the question of how multiple, dynamically propagating crack tips interact. To study this question, Leise and the P.I. considered first the problem of a single finite length anti-plane shear crack growing dynamically under the action of applied crack face tractions. They showed in [3] how one can use the Dirichlet-to-Neumann map for the anti-plane shear elastic wave equation to generalize the method employed previously by the P.I. to solve the problem of a single, accelerating, semi-infinite crack, to the case of a single, growing, finite length crack. They illustrated the method in simulations employing a critical stress intensity factor fracture criterion.

Subsequently, Leise and the P.I. generalized their method for solving a single growing finite length anti-plane shear crack (for which the interacting crack tips are moving apart), to the problem of two semi-infinite cracks dynamically coalescing (two interacting crack tips moving together) and then to the problem of a semi-infinite crack and a finite crack growing and coalescing (containing three interacting crack tips). One of the interesting observations emerging from simulations based upon their analytical solution procedure, as shown in figure 1, is that for a semi-infinite crack/finite crack system with loading only on the semi-infinite crack (as occurs in most experiments in which the main crack is loaded but microcracks forming in front of its crack tips remain stress free), the finite length crack remains nearly stationary as the two cracks coalesce. That is, the main crack merges into the microcrack. The situation is more complicated when both cracks are loaded. Then, as seen in figure 2, whether or not the semi-infinite crack merges into the microcrack or they grow together simultaneously depends upon the strength of the material (as expressed by the magnitude of the critical stress intensity factor) and the size of the microcrack (compared to the length of the loading interval on the semi-infinite crack which plays the role of its crack length).

Leise and the P.I. are currently attempting to extend their solution approach to the more difficult problems of opening mode fracture and interfacial fracture. However, this effort is in the early stages of development and completed results have not yet been obtained.

Temperature Effects in Dynamic Fracture. In collaboration with F. Costanzo, the P.I. has begun consideration of temperature effects in dynamic fracture. This work is motivated by experimental observations of very dramatic temperature rises in the vicinity of dynamically propagating crack tips in brittle polymers. One normally associates such temperature rises with metal plasticity, however Costanzo and the P.I. conjecture that in polymers, the temperature rise is due in part to the frictional type resistance encountered in the fibril drawing out process occurring in the crack tip craze zone described above. Consequently, they are attempting to model this process through the idealization that the heat generation occurs only in the cohesive zone. Thus, they adopt a cohesive zone constitutive law that includes a coupling between the thermal and mechanical fields, whereas in the bulk material, the thermal and

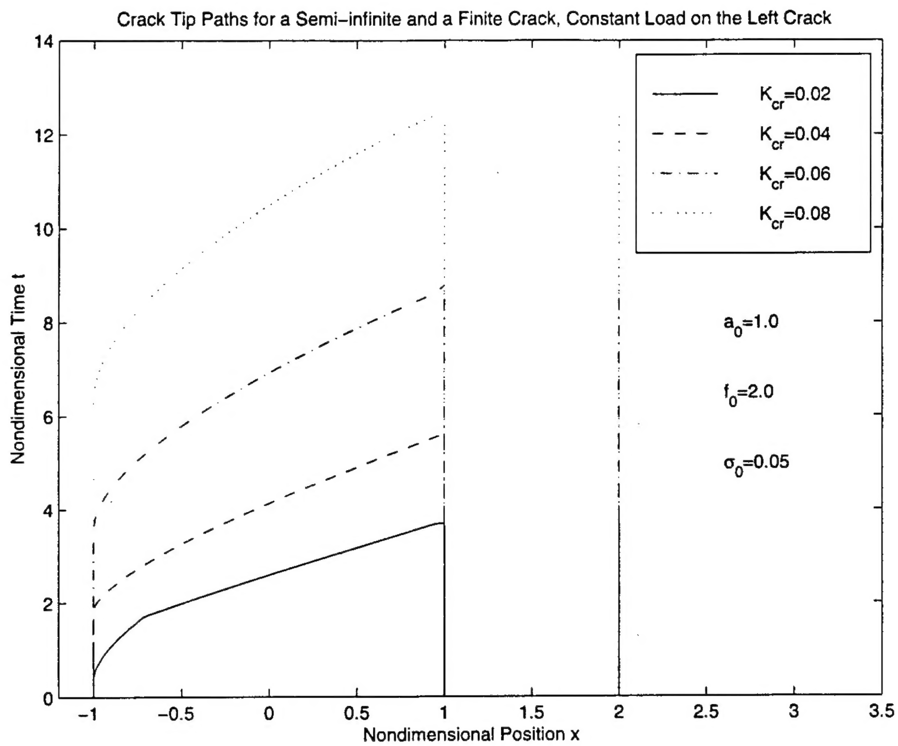

Figure 1: Crack tip paths for an unloaded finite crack near a loaded semi-infinite crack.

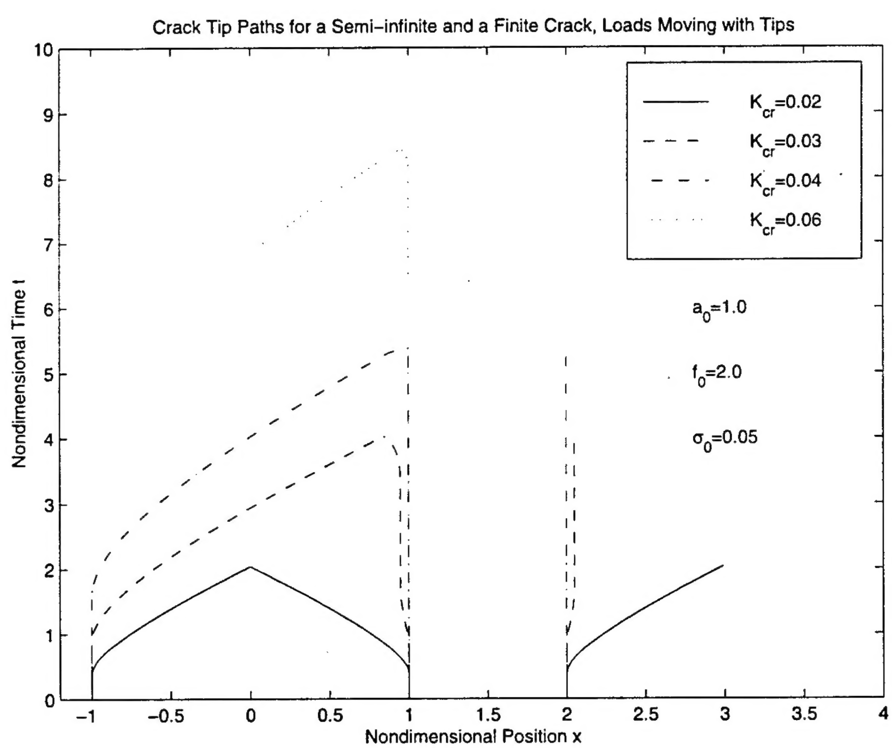

Figure 2: Crack tip paths for a loaded finite crack near a loaded semi-infinite crack.

mechanical fields are uncoupled. Nevertheless, their model does contain a thermal flux term between the cohesive zone and the bulk material. A goal of this effort is to understand the influence of thermal softening in the cohesive zone upon crack growth evolution and the transition from stable crack growth to the unstable regime observed experimentally.

Dynamic Crack Growth in Functionally Graded Material. The P.I. has begun a consideration of dynamic crack growth along an interface in a functionally graded composite material. In such a material, the constitutive properties vary smoothly away from a bi-material interface. Such composite material systems are of increasing importance in technological applications since they offer the prospect of creating laminated composite materials that are not susceptible to the debonding failure occurring at traditional bi-material interfaces due to the mismatch in material properties. The P.I. is considering first a semi-infinite, anti-plane shear crack propagating dynamically along an interface between two half-planes of linear elastic material with shear modulus varying spatially in the direction transverse to the fracture plane. The mathematical difficulty stems from the fact that elastic waves are dispersive in such a medium due to the spatial dependence of the sound speed in the bulk material. To study this problem, the P.I. is performing an asymptotic analysis based upon the assumption that the material properties through out the bulk material are given by an asymptotic series with zero order term corresponding to a homogeneous elastic material. No complete results have yet been obtained on this problem.

Personnel.

The P.I. was the only person supported this past year on the grant funds. However, parts of the research was performed collaboratively with Dr. Francesco Costanzo (Engineering Science, Penn State University) and Dr. Tanya Leise, who this past year was an instructor in the Mathematics Department at Indiana University and who finished her Ph.D. under the P.I.'s direction in December, 1998.

References

[1] Costanzo, F. & J. R. Walton, *A numerical solution technique for a class of integro-differential equations in elastodynamic crack propagation problems*, Comp. Meth. in Appl. Mech. and Engng.**162**, [1998], pp.19-48.

[2] Costanzo, F. & J. R. Walton, *Numerical simulations of a dynamically propagating crack with a nonlinear cohesive zone*, Int. J. Frac. **91**, [1999], pp.373-389.

[3] Leise, T. & J. R. Walton, *Dynamically accelerating cracks part 2: A finite length mode III crack in elastic material*, to appear Quart. Appl. Math..

[4] Leise, T. & J. R. Walton, *Dynamically accelerating cracks part 3: Two Growing and Coalescing Mode III Cracks in elastic material*, submitted for publication.

Interactions.

The P.I. spoke on part of this research in an invited talk to the Prager Symposium at the 1998 Annual meeting of the Society of Engineering Science in October 1998 and in the Applied Mathematics Seminar at Indiana University in November 1998.